

GRB 050408: An Atypical Gamma-Ray Burst as a Probe of an Atypical Galactic Environment

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ABSTRACT

The bright GRB 050408 was localized by HETE-II near local midnight, enabling an impressive ground-based followup effort as well as space-based followup from *Swift*. The *Swift* data from the X-Ray Telescope (XRT) and our own optical photometry and spectrum of the afterglow provide the cornerstone for our analysis. Under the traditional assumption that the visible waveband was above the peak synchrotron frequency and below the cooling frequency, the optical photometry from 0.03 to 5.03 days show an afterglow decay corresponding to an electron energy index of $p_{lc} = 2.05 \pm 0.04$, without a jet break as suggested by others. A break is seen in the X-ray data at early times (at ~ 12600 sec after the GRB). The spectral slope of the optical spectrum is consistent with p_{lc} assuming a host-galaxy extinction of $A_V = 1.18$ mag. The optical-NIR broadband spectrum is also consistent with $p = 2.05$, but prefers $A_V = 0.57$ mag. The X-ray afterglow shows a break at 1.26×10^4 sec, which may be the result of a refreshed shock. This burst stands out in that the optical and X-ray data suggest a large H I column density of $N_{HI} \approx 10^{22} \text{ cm}^{-2}$; it is very likely a damped Lyman α system and so the faintness of the host galaxy ($M_V > -18$ mag) is noteworthy. Moreover, we detect extraordinarily strong Ti II absorption lines with a column density through the GRB host that exceeds the largest values observed for the Milky Way by an order of magnitude. Furthermore, the Ti II equivalent width is in the top 1% of Mg II absorption-selected QSOs. This suggests that the large-scale environment of GRB 050408 has significantly lower Ti depletion than the Milky Way and a large velocity width ($\delta v > 200 \text{ km s}^{-1}$).

Subject headings: gamma-ray bursts: individual (GRB 050408) — galaxies: ISM — stars: formation — galaxies: photometry

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1. Introduction

Leading up to the launch of *Swift* (Gehrels et al. 2004), the astronomical community prepared for massive, multi-wavelength studies of GRBs expected from the satellite. Not long after the launch of *Swift*, HETE-II (Sakamoto et al. 2005) triggered (H3711) GRB 050408 at 16:22:50.93 on 2005 April 8 (UT dates will be used throughout this paper). Soon after its detection, *Swift* triggered a Target of Opportunity on the GRB (Wells et al. 2005). Later, a fading optical afterglow was detected (de Ugarte Postigo et al. 2005) and a redshift of $z \approx 1.236$ was obtained through host galaxy emission lines and afterglow absorption features (Berger et al. 2005; Prochaska et al. 2005a). Radio observations were also obtained but no transient was found (Soderberg 2005). The X-ray afterglow (Wells et al. 2005) was observed over several epochs with *Swift*, leading to an initial inference of a break (Godet et al. 2005), that was later retracted (Capalbi et al. 2005). Finally with all the XRT data, the *Swift* team suggested a jet break at $t_{\text{break}} = (1.2 \pm 0.5) \times 10^5$ sec after the GRB trigger (Covino et al. 2005).

We present light curves of the optical, infrared, and X-ray afterglows in Sections 2 and 3. A detailed analysis of these afterglows is presented in Section 4. An analysis of the optical and X-ray afterglow spectra is presented in Sections 3 and 5. From the absorption in these spectra we are able to place lower limits on the metallicity and the hydrogen column of the host galaxy. Throughout the paper, the concordance cosmology of $\Omega_\lambda = 0.71$, $\Omega_m = 0.29$, and $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used. Though all measurements reported herein are consistent with our preliminary reports in the GCN (GRB Coordinates Network) Circulars, these measurements supersede those in the Circulars.

2. The Optical-Infrared Afterglow

At approximately 18:50 on 8 April 2005, 2.4 hours after the burst, de Ugarte Postigo et al. (2005) detected the optical afterglow of GRB 050408. From this time until 20:10 on April 13, the afterglow was monitored, with many groups reporting preliminary magnitudes and upper-limits in the GCN Circulars¹. Here we report observations from the Keck and Magellan telescopes and perform our own reductions of the *Swift* UVOT data, as described below. All observations are summarized in Table 3.

2.1. Magellan Optical Imaging

Our imaging with the IMACS instrument (Bigelow et al. 1998) on the Magellan I 6.5-m (Baade) Telescope began at 00:12 on 9 April 2005, about 470 minutes after the burst. Two 180-second exposures of the burst field were taken with the R_c filter and three 180-second exposures with the I_c filter. Images were reduced in the standard manner using dome flats acquired on the night of the imaging. We performed photometry using a sample of ten reference stars (Table 1), six objects in the immediate vicinity of the burst previously identified as stars by the Sloan Digital Sky Survey (SDSS), and four additional objects in the field identified as stars by Henden (2005)² but also present in SDSS. We use Sloan magnitudes from the SDSS archive³ of all ten stars to calibrate our R and I instrumental magnitudes to absolute magnitudes in

¹<http://gc.gsfc.nasa.gov/>

²<ftp://ftp.nofs.navy.mil/pub/outgoing/aah/grb/grb050408.dat>

³<http://cas.sdss.org/astro/en/tools/search/>

g' , r' , and i' , and then convert back to the Cousins system using the transform equations of Smith et al. (2002). Based on an astrometric comparison with the 2MASS catalog we find the GRB occurred at position $\alpha(\text{J2000}) = 12^{\text{h}}02^{\text{m}}17^{\text{s}}.328$ and $\delta(\text{J2000}) = +10^{\text{d}}51^{\text{m}}09^{\text{s}}.47$, with an error relative to the International Coordinates Reference System (ICRS) of 250 mas in both coordinates.

2.2. Keck Optical Imaging

Keck imaging was acquired through the UC Target of Opportunity (ToO) program (PI Hurley) on the Keck I 10-m telescope with the dual-beam Low-Resolution Spectrograph Imager (LRIS; Oke et al. 1995). Five 60-second exposures each were taken simultaneously in V and R_c filters (using the D680 dichroic) beginning at 08:11 on 11 April 2005, (2.62 days after the GRB), although because the GRB fell on a chip-gap in one V -band exposure only four were used in the final analysis. The co-added R_c -band image is shown in Figure 1.

Photometry on the Keck images was performed using the same procedure as the Magellan images. Because the imaged field was offset $63''\text{S}$ and $5''\text{W}$ relative to the Magellan exposure, we use a different sample of Henden stars, but the other six sources used for calibration are the same.

We examined the Keck imaging for the possibility that the host galaxy might be detected by comparing the FWHM of the afterglow with those PSFs of field stars. There is no evidence for extension in these images and we thus find no evidence for a host brighter than $V = 27$ mag, which corresponds to $M_V > -18$.

2.3. UVOT Reductions

The *Swift* Ultra-Violet/Optical Telescope (UVOT) observed the field of GRB 050408 starting at 17:07 on 8 April 2005, 44.3 minutes after the burst. A series of images were obtained for the GRB field in various filters. An additional 11 batches of UVOT observations were performed for GRB 050408 in the month following the GRB.

Initial results from these observations were reported by the *Swift*/UVOT team (Holland et al. 2005). They reported a possible detection ($U = 21.30^{+0.45}_{-0.32}$ mag) in a co-added U -band image with a total exposure time of 2927 s, though they note that the detection is marginal. They also reported no detection in other filters and provided limiting magnitudes for the co-added images. However, the times of the center point of the co-added images were not specified.

We retrieved the UVOT data on GRB 050408 from the *Swift* Quick-look archive⁴ and performed photometry using the calibration results and the photometry recipe for *Swift*/UVOT from Li et al. (2005). For the U -band data, a careful inspection of all the data combined from the first two days after the burst does not convincingly demonstrate the existence of any object down to a limiting magnitude of $U = 21.40$ mag. We also re-analyzed the five V -band exposures from UVOT, and find no detections to the limiting magnitudes (3σ) listed in Table 2.

⁴<http://swift.gsfc.nasa.gov/cgi-bin/sdc/ql?>

2.4. Infrared Photometry

Infrared imaging of the field of GRB 050408 from both the southern (CTIO) and northern (Mt Hopkins) 2MASS 1.3m telescopes was obtained on the first night of the burst. The ANDICAM⁵ instrument mounted on the 1.3m telescope at Cerro Tololo Inter-American Observatory (CTIO) started observations at 03:15 on 9 April 2005. Images were obtained with a dual-channel camera that allows for simultaneous optical and IR imaging. Both optical and IR images are double-binned in software to give an optical pixel scale of 0.27 arcsec pixel⁻¹ and an IR pixel scale of 0.37 arcsec pixel⁻¹. While standard optical integrations are underway, the ANDICAM instrument allows IR images to be “dithered” by the slight adjustment of three tilt axes of an internal mirror. A combination of 6 telescope re-points and 5 internal dithers were used to obtain 6 separate 360-second *I*-band images and 30 separate 60-second *J*-band images per data set.

The Peters Automated Infrared Imaging Telescope (PAIRITEL⁶) started observations at 9 April 04:03:27, 11.7 hr after the GRB. *J*, *H*, and *K_s* band images were acquired simultaneously with 3 NICMOS3 arrays in double correlated reads with individual exposure times of 7.8 sec. Each image consists of a 256×256 array with a plate scale of 2 arcsec pixel⁻¹. In a given epoch the telescope is dithered every 3 exposures, allowing for a sky frame appropriate for every image, derived from a star-masked median stack of images before and after, to be created by the pipeline software. The offsets between images are determined by a cross-correlation and reduced images were then subsampled and stacked with a resolution of 1 arcsec pixel⁻¹. The effective seeing over all the epochs was approximately 2.3'' FWHM. A stack of all offset-shifted epochs revealed a faint IR source at the location of the optical afterglow.

On the stacked images, we ran SExtractor⁷ to find the instrumental magnitudes in a 2.5 arcsec radius aperture. These magnitudes were used to find an absolute zeropoint uncertainty (0.02 mag in all bands), using more than 20 stars in common stars with the 2MASS catalog in each band. The transient was easily detected and well isolated in *H* and *K_s* but was marginally blended in the *J*. As such, we used the average transient position from the *H* and *K_s* image to determine the *x,y* position in the *J* band image. Fixing this center, we used IRAF/PHOT to determine the aperture magnitude (with the 2MASS zeropoint). For field stars, we confirmed that IRAF/PHOT and SExtractor gave the same results within the errors. The *JHK_s* magnitudes from PAIRITEL are reported in Table 3.

2.5. Photometry from the Literature

To produce light curves, numerous additional reported measurements were taken from the GCN Circulars. Optical measurements (including upper limits) were retrieved from the circulars in all bands where detections were reported: *B*, *V*, *R*, *I*, *J*, and “*Z*” (Flasher et al. 2005, interpreted as Sloan *z'*) via GRBlog⁸ and the resulting table was screened for errors caused by the automatic parsing of the circulars. We removed duplicate reports, as well as one observation from Milne et al. (2005), which suggested a 1 magnitude brightening in the *I* band more than 0.5 days after the burst (this was not seen in any other bandpass). We

⁵<http://www.astronomy.ohio-state.edu/ANDICAM> ANDICAM is operated as part of the Small and Moderate Aperture Research Telescope System (SMARTS) consortium. <http://www.astro.yale.edu/smarts>

⁶<http://www.pairitel.org>

⁷<http://sextractor.sourceforge.net/>

⁸<http://grad40.as.utexas.edu/grblog.php>. GRBlog provides a query mechanism for GCN Circulars and their meta-data.

also culled the *B*-band measurement from Milne et al. (2005), which was brighter in flux than simultaneous measurements at longer wavelengths. We replaced data that had been superseded by later analysis for the UVOT limiting magnitudes and Magellan observations, and added the Keck and PAIRITEL magnitudes.

All observations used in our subsequent fitting are listed in Table 3.

3. The X-ray Afterglow

The *Swift* XRT (Burrows et al. 2000) began observations of GRB 050408 at 16:34 on 8 April 2005, approximately 672 sec after the HETE-II trigger (Sakamoto et al. 2005). The XRT operates in a variety of different observing modes, and many were used throughout the observations. Unfortunately, the first 1.8 ks of observations were spent on a certain mode (the “Low Rate Photodiode” mode) that was not useful for this GRB. The “Photon Counting” mode observations, which retain full imaging and spectroscopic resolution, began at 17:05:24. As reported by Wells et al. (2005), these XRT data revealed a fading X-ray source in the HETE-II error circle. In the ensuing weeks, *Swift* observed the GRB a dozen times. A log of the Photon Counting mode observations is found in Table 4.

We have obtained the XRT data from the *Swift* archive, and have analyzed them to determine the temporal and spectral properties of the X-ray afterglow emission. We briefly review the data reduction, and then we discuss the characteristics of the X-ray afterglow.

3.1. *Swift* Data Reduction

Using the Level 1 data from the *Swift* archive, we ran the `xrtpipeline` script packaged with the HEASoft 6.0 software supplied by the NASA High Energy Astrophysics Science Archive Research Center⁹. We used the default grade selection (grades 0 to 12) and screening parameters to produce a Level 2 event file re-calibrated according to the most current (as of 1 November 2005) calibration files in the *Swift* database¹⁰. To produce images for source detection, we used the `xselect` software (also part of HEASoft 6.0), with a filter to include only counts in PI channels 30–1000 (corresponding to photon energies of 0.3–10 keV). The PI channel to photon energy conversion was accomplished with the redistribution file `swxpc0to12_20010101v007.rmf` from the calibration database. The effective area of the XRT at the position of the afterglow candidate was determined with the `xrtmkarf` tool, using the correction for a point source.

Although a source extraction region of 20 pixels ($47''.2$) in radius is recommended in the XRT Data Reduction Guide¹¹, we chose a smaller extraction region (8 pixels) to mitigate the complications due to a nearby source (designated X1) located about $37''.5$ to the North. Although negligible in the early observations, this source can contribute a moderate amount of the flux at the location of the GRB in the late observations. Figure 2 shows $3' \times 3'$ images of the XRT data from the first and eleventh observations. We discuss the regions A and B below.

To quantify the effects of using a smaller extraction region, we used the XRT simulator at the ASI

⁹<http://heasarc.gsfc.nasa.gov/>

¹⁰<http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/>

¹¹http://heasarc.gsfc.nasa.gov/docs/swift/analysis/xrt_swguide_v1.2.pdf

Science Data Center¹² to investigate the XRT point spread function (PSF). We simulated a very bright X-ray source with a power-law spectrum with a photon index of 1.7 and a column density of $N_H = 10^{20} \text{ cm}^{-2}$. An extraction radius of 20 pixels was found to contain $\sim 90\%$ of the total counts, and an extraction radius of 8 pixels contained $\sim 70\%$ of the total counts. An 8 pixel radius region located $37''.5$ from the source position contained $\sim 3\%$ of the total counts.

We can therefore represent the counts (C) in region A as

$$C_A = 0.7C_{\text{GRB}} + 0.03C_{\text{X1}} + C_{\text{bkg}}$$

where C_{bkg} is the number of expected background counts in region A. We use a large, source-free region to the West of the GRB to estimate the background count density in each observation. Using a similar expression for the counts in region B, we can solve for the intrinsic GRB count rate in each observation. We list the relevant quantities for each observation (with the first subdivided into a number of intervals) in Table 4.

3.2. X-ray Afterglow Spectrum

We investigate the spectral shape of the afterglow emission using a redshifted powerlaw model with two absorption components — a Milky Way component set at the Galactic value of $N_H = 1.81 \times 10^{20} \text{ cm}^{-2}$, and a redshifted component local to the GRB with N_H allowed to vary. We fix the redshift of the powerlaw and the host galaxy absorption at $z = 1.236$.

The spectral fitting was performed in Sherpa (Freeman et al. 2001) with a hybrid Monte Carlo/Levenberg-Marquardt method. We group the data to have at least 15 counts per bin and fit the background-subtracted spectra using χ^2 minimization with Gehrels weighting (Gehrels 1986). To account for the contributions from the source in region B, we fit a powerlaw to the spectrum from this source in observation 11 (which has a relatively strong signal from region B and a weak signal from region A). We include this powerlaw as a fixed component to our model of the GRB spectrum, with a normalization of 3% of the best fit (see Section 3.1).

We investigate separately the 0.3–10 keV data before t_{break} (observations 1a and 1b) and after t_{break} (observations 1c–1m, 2–12), where $t_{\text{break}} = 1.26 \times 10^4 \text{ sec}$ (see Section 4.2), but we find only marginal evidence for differences in the best fit model parameters, which are listed in Table 6. Figure 9 plots the χ^2 contours as a function of the redshifted powerlaw photon index Γ and redshifted N_H for both sets of data; contours are drawn at 68%, 90%, 95%, and 99%. Our best fit models had χ^2/dof of 17.2/22 (before t_{break}) and 26.1/30 (after t_{break}).

As the plot shows, the host galaxy column density is poorly constrained and is correlated with the powerlaw index. The XRT bandpass of 0.3–10 keV corresponds to a rest frame energy range of 0.67–22.4 keV. Given the low statistical quality of the data, and the fact that broadband absorption is most prominent below about 2 keV, it is not surprising that the XRT data do not constrain the column density very well.

We investigate any intrinsic spectral differences before and after t_{break} by considering only data above 2 keV, which is relatively insensitive to the absorbing column to the GRB. We perform a 2-sided Kolmogorov-Smirnov test on the energy channel (PI) cumulative histograms of the data before and after the break. There

¹²<http://www.asdc.asi.it/simulator/swift/>

is only a 0.003 probability that they are drawn from the same parent distribution. To quantify this in terms of a model, we perform a joint fit to the two data sets. The model consists of a simple powerlaw for each spectrum, and the free parameters are the photon index before the break, the difference in photon index from before until after the break, and the normalizations of the powerlaws. We find an acceptable fit with a χ^2/dof of 11.7/23. For these 2–10 keV data, the best fit powerlaw index before t_{break} is 2.3 ± 0.5 , consistent with the best fit index found from the entire 0.3–10 keV band (Table 6). The difference in spectral index before and after t_{break} is found to be 1.0 ± 0.6 . We plot the minimum χ^2 found as a function of this difference in Figure 5.

To estimate the X-ray flux of the GRB, we use the best fit model before t_{break} . We need to correct the integrated model flux since the response files generated by the XRT reduction software assume an extraction radius of 20 pixels, in which 90% of the flux from a point source is contained. Our 8 pixel radius extraction region contains only 70% of the flux from a point source (see Section 3.1) so we multiply the best fit model flux by 1.29. The observed, absorbed flux in the 0.3–10 keV band is $9.0^{+4.4}_{-2.8} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. Corrected for Galactic absorption and absorption by the host galaxy, the observed flux is $15.0^{+7.4}_{-4.6} \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. This would correspond to the emitted flux in the 0.67–22.4 keV band. Based on this model, the countrate to flux conversion is $38.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ count}^{-1}$ (absorbed) and $63.7 \times 10^{-12} \text{ erg cm}^{-2} \text{ count}^{-1}$ (unabsorbed).

4. Afterglow in the Context of the Synchrotron Shock Model

4.1. Optical Afterglow Fitting

We converted the magnitudes in Table 3 to absolute flux densities using zero points from Fukugita et al. (1995) and Cohen et al. (2003), assuming Cousins zero points for all *R*- and *I*-band measurements. We then fit these data in flux-time space with various power-law models of the basic form

$$F = S \left(\frac{t}{t_c} \right)^{-\alpha}.$$

Where t_c is an arbitrary constant (defined to be 1 day) that sets at what time the measured flux is equal to S . Data without quoted errors were ignored during fitting. We ignore the possible contribution of a constant host galaxy flux to the optical/IR afterglow light: this appears justified by the lack of any extended emission in the latest Keck imaging.

We fit three different models to the data: an unbroken power law where α is constrained to be the same in each filter, an unbroken power law where α is unconstrained, and a broken power law where α and t_{break} are constrained to be the same in each filter. The data, owing largely to the steep decay implied by the *V*-band measurements of Milne et al. (2005), formally prefer a model where the *V* band decay slope differs from that of the slopes in *R* and *I*. However, a common power law still fits the data well: $\chi^2/\text{dof} = 23.6 / 24$ (versus 14.7 / 21 for a variable power-law). The broken power-law model offers negligible improvement in χ^2 over an unbroken fit and is excluded to 44% confidence.

If we ignore the peculiar slope of the *V*-band data (physically we do not expect such behavior, and our own measurements do not show a changing spectral index) and look only at the unbroken, common-alpha model, we derive a best-fit value of $\alpha = 0.789 \pm 0.033$ (see Figure 6). Using the linear S factors and correcting for Galactic extinction (Schlegel et al. 1998), we then form a simple broadband spectrum (Figure 7) and fit a simple powerlaw to this as well. This is found to describe the data well ($\chi^2/\text{dof} = 3.19/5$); the resulting value of the spectral index, defined at $F_\nu \propto \nu^{-\beta}$, is then $\beta = 1.30 \pm 0.10$.

Assuming a synchrotron source and certain properties of the medium in the vicinity of the progenitor, these values for the decay constant can be used to calculate p , the electron power spectrum (Sari et al. 1998). The resulting p -values for a homogeneous medium are $p_{lc} = 1 + 4\alpha/3 = 2.05 \pm 0.04$ (from the light curves) and $p_{bb} = 2\beta_{bb} + 1 = 3.61 \pm 0.19$ (from the broadband spectrum). These values are inconsistent, and therefore difficult to reconcile with the simplest synchrotron model. As such, we tried to fit a variety of afterglow models in the context of different spectral regimes and external environments.

Following Price et al. (2002), we identify three GRB afterglow models with different predictions about the relationship between the light curve and spectral index: (1) isotropic expansion into a homogeneous medium, (2) isotropic expansion into a wind-stratified medium, and (3) collimated expansion into a homogeneous or wind-stratified medium. The three models share a common form for the relation between these parameters, $\alpha + b\beta + c = 0$, where the values of b and c depend both on the model and whether the cooling frequency has passed through the optical and NIR bands of our observations, for a total of six possible closure relations.

For each relation, we calculate the value of the closure parameter $\alpha + b\beta = c$ and its uncertainty, as well as the predicted electron energy spectrum index p , to compare the compatibility of various models to the observations.

All models except the standard model (an isotropic medium with $\nu_c > \nu$) predict a value of $p < 2$, a situation that is unphysical unless there is a high-energy cutoff in the electron energy spectrum. Furthermore, based on the calculated closure parameters, all six relations are excluded with a confidence of at least 4σ —the spectral index predicted by these models is much less than that observed in our optical and broadband spectra. However, we note that the spectral index is not corrected for host-galaxy reddening, which the optical spectrum (discussed in Section 5) suggest may be significant.

We examine the effect of extinction by calculating the predicted value for the unextinguished spectral index $\beta = -(\alpha + c)/b$ for each model and fit the observed photometric spectrum for extinction at the host redshift, assuming a value of $R_V = 3.1$. This provides dramatic improvement for all models, with the best fit given by the (equivalent) ISM-R and Wind-R models (‘R’ designating that the cooling frequency is redward of the optical band; i.e. $\nu_c < \nu$), for which $\chi^2/\text{dof} = 5.31/5$. For the standard assumption of $\nu_c > \nu$, we derive a value of $\chi^2/\text{dof} = 7.82/5$ for a homogeneous medium or $\chi^2/\text{dof} = 11.3/5$ for a wind-stratified medium. The jet models do not have an acceptable χ^2/dof whether the cooling frequency is blueward or redward of the optical band. The inferred value of p depends only on α and the model, and is not extinction-dependent. As such, only the standard homogeneous-medium model is consistent with an electron energy spectrum that is not cut off at high energies.

Making no assumptions about the unextinguished spectral index and fitting for the best values of β and A_V , the optimum fit is an unextinguished fit: $A_V = 0$ and $\beta = 1.30$, for which $\chi^2/\text{dof} = 3.19/4$. This is not surprising given the data: the observed spectral slope is slightly steeper in the near-IR than in the optical, whereas dust would be expected to steepen the spectral index in the optical more than in the near-IR. However, the data are not inconsistent with the extinguished model: most of the discrepancy is due to the single K -band observation.

Confidence contours for fits to the broadband data, varying β and A_V , are shown in Figure 8. From this plot we see the strong covariance between the afterglow spectral index and extinction— and that while a steep-index, low-extinction model is preferred, smaller values of β are also consistent with observations if there is sufficient extinction. Constraining β to the standard model of a homogeneous medium with $\nu_c > \nu$, by which the afterglow is best fit, we find $A_V = 0.57$ mag. While formally the best fit yields $A_V = 0$ mag, the model consistent with the afterglow decay (yielding $A_V = 0.57$ mag) is within 1σ of the best fit.

4.2. X-Ray Observations of an Early Light-Curve Break

We attempted to model the GRB count rate with a simple power-law decline in time, but that gave a statistically unacceptable fit ($\chi^2/\text{dof} = 51.2/21$ corresponding to a probability of 0.025%). We next tried a broken power-law model of the form

$$R_{\text{x,GRB}}(t) = \begin{cases} At^{-\alpha_{\text{x},1}} & t \leq t_{\text{break}} \\ A't^{-\alpha_{\text{x},2}} & t > t_{\text{break}} \end{cases}$$

where $R_{\text{x,GRB}}(t)$ is the GRB X-ray countrate and $A' = A(t_{\text{break}})^{\alpha_{\text{x},2}-\alpha_{\text{x},1}}$. We performed the model fitting in Sherpa, using a hybrid Monte Carlo/Levenberg-Marquardt optimization method and a χ^2 statistic. This hybrid method randomly samples the parameter space 10000 times (the Monte Carlo part) for initial values and then uses a Levenberg-Marquardt algorithm to find the local fit-statistic minimum nearest to the starting point. Using this method, we found an acceptable fit ($\chi^2/\text{dof} = 23.4/19$) whose parameters are listed in Table 5. The data from Table 4 and the best-fit model are plotted in Figure 3. We note that the value of our break parameter $t_{\text{break}} = (1.26_{-0.36}^{+1.19}) \times 10^4$ sec is significantly lower than the value of $(1.2 \pm 0.5) \times 10^5$ sec found by Covino et al. (2005). This is most likely due to their fitting algorithm finding a local minimum near this value. Figure 4 plots the minimum χ^2 found as a function of the parameter t_{break} .

5. Absorption Spectrum

5.1. Observations and Reductions

An optical spectrum of GRB 050408 was obtained under program GN-2004A-Q-4, a Band 1 rapid ToO program (with carry-over status) executed in the queue at 06:29 on 9 April 2005 April using the Gemini North 8-m telescope with GMOS (Hook et al. 2004). We used a 0.75 arcsecond slit, the R831 grating, OG515 order-blocking filter, and set the central wavelength to 7330Å. Standard CCD processing and spectrum extraction were accomplished with IRAF using a 1.16" aperture. The data were extracted using the optimal algorithm of Horne (1986). Low-order polynomial fits to calibration-lamp spectra were used to establish the wavelength scale. Small adjustments derived from night-sky lines in the object frames were applied. Using techniques discussed in Wade & Horne (1988) and Matheson et al. (2000), we employed IRAF and our own IDL routines to flux-calibrate the data and to remove telluric lines using the well-exposed continua of the spectrophotometric standard Feige 34 (Oke 1990).

5.2. Spectral Index and Host Galaxy Dust

Over the small wavelength range of $\sim 6280 - 8400\text{\AA}$, we were able to fit a powerlaw spectrum to our spectrum of GRB 050408. Correcting only for the Galactic reddening of $A_V = 0.081$ mag (Schlegel et al. 1998), we find $\beta_{\text{spec}} = 2.11 \pm 0.29$ and $p_{\text{spec}} = 2\beta_{\text{spec}} + 1 = 5.22 \pm 0.58$. The errors for these measurements are statistical only. In reality, differential light loss due to the slit position not being at the parallactic angle (Filippenko 1982) and the small wavelength range will contribute additional errors. The p -value derived from the spectrum is statistically inconsistent with that derived from both the broadband spectrum and light-curve decay found in Section 4.1, $p_{\text{bb}} = 3.61 \pm 0.19$ and $p_{\text{lc}} = 2.05 \pm 0.044$. However the p -value derived from the spectrum is much closer to the p_{bb} (within 3σ) than p_{lc} ($> 5\sigma$).

As discussed in Section 4.1, it is possible that dust in the host galaxy of GRB 050408 is extinguishing

the spectrum, causing the deviant spectral shape. We performed our same fitting analysis for the optical spectrum as above, except allowing a dust component at the redshift of the host galaxy. Doing this, we find that an extinction of $A_V = 1.18 \pm 0.09$ mag yields a p -value consistent with that found with the light curve. The best value of $A_V = 1.18$ mag yields $\beta_{\text{spec,dust}} = 0.53 \pm 0.11$ and $p_{\text{spec,dust}} = 2.05 \pm 0.23$. This suggests a significant source of dust in the host galaxy. As shown in Section 4.1, the broadband spectrum is consistent with significant host-galaxy extinction, but not as much as the GMOS spectrum suggests. Again, the discrepancy between these two values are attributed to the small wavelength range of the optical spectrum.

5.3. Absorption Line Measurements

Figure 10 presents the Ti II, Mg I, Fe I, and [O II] transitions observed in our GMOS spectrum of the afterglow. We have fit a local continuum at the position of each transition and measured the rest equivalent width W_r of each feature (Table 7). The errors only include statistical uncertainty. For the weakest transitions, uncertainty in continuum placement will give an error comparable to the statistical error.

Consider the Ti II measurements first. The W_r values for the four transitions are consistent with the relative oscillator strengths and indicate the Ti II $\lambda\lambda 3242, 3384$ profiles are saturated. We can place a conservative lower limit to the Ti II column density by adopting the W_r value from Ti II $\lambda 3384$ and ignoring corrections for line-saturation. This gives $N_{\text{TiII}} > 10^{13.2} \text{ cm}^{-2}$. This value is consistent with the column density derived from Ti II $\lambda 3230$ assuming that transition lies on the linear curve-of-growth.

Both the equivalent width and the implied ionic column density are extraordinary. Although Ti^+ is the dominant ion in neutral gas, Ti is highly refractory (e.g. Savage & Sembach 1996) and only a trace amount ($\sim 1\%$) is observed in the gas-phase of the Milky Way. Therefore, the observed equivalent widths for Ti II $\lambda 3384$ along Milky Way sightlines are $\approx 10 \text{ m\AA}$ (Pettini et al. 1995; Welsh et al. 1997; Prochaska et al. 2005b), i.e. $50\times$ smaller than that observed in this GRB afterglow. Even sightlines with $N_{\text{HI}} \sim 10^{22} \text{ cm}^{-2}$ have equivalent widths $W_r < 50 \text{ m\AA}$ (Welsh et al. 1997). Therefore, the Ti II column density along the sightline through the GRB host galaxy exceeds the largest values observed for the Milky Way by an order of magnitude. The few damped $\text{Ly}\alpha$ systems with Ti II detections also have rest equivalent widths $< 50 \text{ m\AA}$ (Dessauges-Zavadsky et al. 2002). Similarly, the LMC has sightlines with equivalent widths $\lesssim 100 \text{ m\AA}$ (Caulet & Newell 1996).

Let us now consider the implications for the physical conditions within the ISM of the GRB host galaxy. The gas-phase Ti II column density that one observes is the product of three factors (ignoring ionization corrections) – (a) the gas column density N_{HI} ; (b) the metallicity of the gas $[\text{Ti}/\text{H}] \equiv \log[N(\text{Ti})/N_{\text{HI}}] - \log[N(\text{Ti})/N_{\text{HI}}]_{\odot}$; and (c) the depletion factor $D_{\text{Ti}} \equiv -\log[N(\text{Ti})_{\text{gas}}/N(\text{Ti})]$ – specifically:

$$N(\text{TiII}) = N_{\text{HI}} + [\text{Ti}/\text{H}] - D_{\text{Ti}} - 7.06$$

where the constant factor accounts for the solar abundance of Ti (i.e. 12 - 4.94). The first result is that the gas column density must be large along the afterglow sightline. Even for the unrealistic situation that the gas has solar metallicity and is entirely undepleted, we have $N_{\text{HI}} > 10^{20.3} \text{ cm}^{-2}$, i.e. the sightline satisfies the H I threshold which defines a damped $\text{Ly}\alpha$ system (e.g. Prochaska et al. 2005b). Such a large H I column density is consistent with previous measurements in GRB afterglow spectra (e.g. Vreeswijk et al. 2004). The value implies the burst originated in a gas-rich and presumably star-forming galaxy.

Second, the fact that GRB 050408 shows a much higher Ti II equivalent width than the Milky Way indicates that $[\text{Ti}/\text{H}] - D_{\text{Ti}}$ is 1 dex higher in the host galaxy. Unless the GRB gas has super-solar metallicity, the observations argue that the gas has a significantly lower depletion level than the Milky Way ISM. Interestingly, this result matches the conclusion for several other afterglow spectra (Savaglio & Fall 2004; Vreeswijk et al. 2004; Chen et al. 2005). The lower depletion of Ti could be the result of several factors. First, the dust at high redshift may have a different composition (e.g. much less Ti oxides) than the local universe. Second, the galaxy may be too young for the gas to have been significantly depleted from the gas-phase. Third, processes local to the GRB may have resulted in the destruction of the dust grains. These could include UV photodissociation from OB stars in a star forming region and/or supernova shocks or even a prompt UV flash associated with the GRB event (Waxman & Draine 2000).

To this point, we have restricted the discussion to a comparison of Ti II between GRB 050408 and the Milky Way. Therefore, one might question whether the Milky Way has an unusual Ti depletion level and that the characteristics of GRB 050408 are therefore not particularly unique. To investigate this point, we performed the following analysis to further assess the nature of the Ti II detection. First, we compiled the set of strong ($W_r > 1.3\text{\AA}$) Mg II systems with absorption redshift $z < 1.8$ identified by Prochter et al. (2004) in the Sloan Digital Sky Survey Data Release 3 quasar sample. These quasar absorption line systems are expected to arise in a variety of environments including galactic disks (Rao & Turnshek 2000), galactic halos (Steidel & Hamilton 1993), and possibly galactic superwinds (Bond et al. 2001). The key point is that the systems were selected to have very strong metal-line Mg II absorption and also strong Fe II absorption, i.e. metal-lines with large W_r . We then measured the W_r in a 5 pixel bin centered at the expected positions of Ti II $\lambda\lambda 3242$ and 3384 . Of the sample of 4450 Mg II systems, only 120 showed a 3.5σ detection at the position of either Ti II transition. Furthermore, 2/3 of these ‘detections’ were related to coincidental absorption lines (e.g. Mg II systems at higher redshift) or poorly subtracted sky-lines.

Figure 11 plots a histogram of the probable detections for Ti II $\lambda 3384$. Our analysis indicates that fewer than 1% of the sightlines with strong Mg II absorption have correspondingly strong Ti II absorption. Furthermore, only a handful of the positive detections have W_r as large as GRB 050408 ($< 0.1\%$ of all strong Mg II absorbers). It is evident, therefore, that the Ti II absorption observed for GRB 050408 is special to the GRB event.

Finally, consider the observation of Mg II and the possible detection of Fe I. Neither of these ions are dominant in H I regions because their ionization potential is less than 1 Ryd. Therefore, it is difficult to infer physical conditions from these features. On the other hand, the strength of Mg I is remarkable. Because the line is highly saturated, its equivalent width gives a lower limit to the velocity width of the gas $\delta v > (W_r/\lambda_r)c > 150 \text{ km s}^{-1}$. We note that the saturated absorption features in the afterglow spectrum of GRB 020813 also indicate a velocity width $\delta v > 200 \text{ km s}^{-1}$ (see also Fiore et al. 2005). This appears to be a common feature of GRB afterglow spectroscopy (Vreeswijk et al. 2004; Ledoux et al. 2005) although not a generic feature (Chen et al. 2005). This is not, however, an expected result in terms of the likely dynamics of the galaxy. For example, assume the GRB originates near the center of a rotating disk galaxy with circular velocity v_c . The maximum velocity width one would measure is $\delta v = v_c$ and only for an edge-on sightline. The average value, of course, would be significantly lower. Unless these galaxies are relatively massive – an assertion not supported by their relatively low luminosities (Le Floc’h et al. 2003) – then the observations suggest an additional velocity field, presumably related to the GRB environment or event.

6. Discussion

6.1. Afterglow Behavior

The synchrotron shock model (Sari et al. 1998) has thus far been very successful at describing afterglow data. The addition of breaks from a reverse shock, cooling break, and the jet break has further explained several afterglows. However there are already known inconsistencies with this model.

GRB 030329 has shown several rebrightenings in its optical light curve which can not be explained by the synchrotron shock model. Suggested explanations for these rebrightenings include the refreshed shock model (Panaitescu et al. 1998; Kumar & Piran 2000).

The current models of GRB afterglows relying on synchrotron radiation from a relativistic shell colliding with an external ISM does not fully explain the afterglow of GRB 050408 without additional considerations, such as host-galaxy extinction. The p -value derived from the afterglow decay, $p_{lc} = 2.05 \pm 0.04$, is inconsistent with the p -values derived from the broadband and GMOS spectra, $p_{bb} = 3.87 \pm 0.20$ and $p_{spec} = 5.22 \pm 0.58$. The high p -values derived from the GMOS spectrum are determined from a small wavelength coverage and the errors on the value are appropriate for the wavelengths shown in the spectrum, but this region of the spectrum may differ significantly from the global spectral shape. With this consideration, we believe the broadband and GMOS spectra have consistent p -values, which are still inconsistent with the afterglow decay p -value.

The most obvious physical situation that would cause a discrepancy between the afterglow decay and the afterglow spectrum is dust (since the decay should not be affected by this, but the spectrum will be). In Section 5, we show that the absorption spectrum is consistent with the afterglow decay if we assume a large ($A_V = 1.18$) host-galaxy extinction. This value is somewhat larger than that from the broadband spectrum ($A_V = 0.567 \pm 0.044$), but this is not surprising given the discrepancy between the observed spectra.

The break observed in the X-ray afterglow is intriguing. This change from a shallow ($0.2 < \alpha < 0.8$) to slightly steeper ($1 < \alpha < 1.5$) powerlaw index has been very common in *Swift* bursts (Nousek et al. 2005). Although the break may be associated with a physical mechanism associated with the afterglow (such as a minimum frequency break), other possibilities include energy reinjection. Our lack of excellent sampling near the time of the break and the overall low X-ray flux does not allow us to make further predictions.

6.2. Hydrogen Column and Ti II Abundance

From Section 3.1, we found that the amount of N_H found by fitting the X-ray spectrum is $N_{HI} \approx 10^{22} \text{ cm}^{-2}$. Examining the optical absorption spectrum in Section 5, we found $N_{HI} > 10^{20.3} \text{ cm}^{-2}$. The large equivalent widths associated with Ti II in our absorption spectrum of GRB 050408 suggest a large hydrogen column, a super-solar metallicity, and/or a lower Ti depletion than the Milky Way. A super-solar metallicity seems unlikely given the redshift of the galaxy of $z = 1.236$. We are then forced to look at the hydrogen column and Ti depletion. If there is any depletion of Ti or if the Ti/H ratio is sub-solar in the host galaxy, both of which are likely, then a value of $N_{HI} \approx 10^{22} \text{ cm}^{-2}$ is quite reasonable.

The strong Ti II lines are an interesting feature. Ti II lines as strong as those in the afterglow of GRB 050408 are very rare in Mg I absorption systems ($\sim 0.1\%$). However, these lines are present in other GRB afterglow spectra. This indicates that the physical properties of the environment of these GRBs that create the strong lines are linked to the GRB-progenitor formation or the GRB-progenitor affected

environment. It appears that a low Ti depletion is somehow linked to the formation of massive stars, the environment created around such massive stars, or perhaps the event itself.

6.3. Line Velocities

The large velocities ($v \approx 150 \text{ km s}^{-1}$) implied by the absorption lines in the spectrum of GRB 050408 are not easily explained by the kinematics of the host galaxy. Although it is possible that the host is a very massive galaxy (although unlikely considering the luminosity of $M_V > -18$), another scenario is that the velocity is local to the GRB. The presumed progenitors to long-duration GRBs, Wolf-Rayet stars, are known to have large winds, and therefore, large line velocities associated with them (Gull et al. 2005). Mirabal et al. (2003) saw distinct systems of lines offset by ~ 450 , ~ 1000 , and $> 1000 \text{ km s}^{-1}$ from the host redshift, which they interpreted as a shell nebula from a Wolf-Rayet progenitor surrounding the GRB. The resolution of our spectrum is too low to see distinct components within our lines, however, we can safely say that there is no strong, distinct component at $\sim 3000 \text{ km s}^{-1}$ relative to the host galaxy.

7. Conclusions

GRB 050408 is a particularly interesting object showing both the consistency of predicted models and showing new and extreme cases of physical phenomena. In particular, we have shown:

- The synchrotron electrons had energy index of $p \approx 2$, the lower limit of physically acceptable systems (Mészáros & Rees 1997; Sari et al. 1998). This is supported directly by the optical-NIR afterglow decay and the X-ray spectrum. There is also indirect support (assuming particular models) from the optical spectrum, the optical-NIR broadband spectrum, and the X-ray afterglow decay.
- The X-ray afterglow shows a break at 1.26×10^4 sec after the burst. This break is not attributed to a jet break. One possible explanation is continued energy injection.
- The hydrogen column is very large ($N_{\text{HI}} \approx 10^{22} \text{ cm}^{-2}$). The optical spectrum also showed one of the most extreme Ti-absorption systems observed. The combination of these facts suggest that there is an incredibly low amount of Ti depletion in the environment of GRB 050408. This has been noted for other GRBs, suggesting that low Ti depletion is linked to GRB environments, possibly due to high-mass star formation, the environments of newly formed supernova and GRB remnants, or dust destruction from the GRB.
- The large velocities associated with the absorption lines are not easily explained by the kinematics of the host galaxy. For a systemic velocity of $v \approx 150 \text{ km s}^{-1}$, a large mass (and possibly a special geometry) is needed. However, we have shown that the host of GRB 050408 is faint $M_V > -18$, comparable to the LMC. This suggests that the velocities originate close to the progenitor, either from a wind from the Wolf-Rayet progenitor star or older supernova explosions close to the progenitor.

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Table 1. SDSS Reference Stars

SDSS Obsid	RA	Dec	g' (Mag)	r' (Mag)	i' (Mag)	Images applied to
587734893827063893	180.50328	10.804996	18.935 ± 0.010	17.583 ± 0.006	16.952 ± 0.005	M ^a
587732772665294967	180.53813	10.823279	18.827 ± 0.008	18.370 ± 0.007	18.208 ± 0.008	M
587732772665294873	180.54322	10.860261	18.944 ± 0.009	18.601 ± 0.008	18.474 ± 0.010	M, K ^b
587734893827129348	180.55899	10.783250	17.741 ± 0.005	17.412 ± 0.005	17.280 ± 0.006	M
587732772665294997	180.59562	10.899296	18.796 ± 0.008	18.484 ± 0.008	18.377 ± 0.009	K
587732772665295483	180.58477	10.862593	22.557 ± 0.117	21.092 ± 0.048	20.152 ± 0.031	M, K
587732772665295451	180.57622	10.856447	23.182 ± 0.202	22.027 ± 0.107	21.520 ± 0.098	M, K
587732772665295418	180.56102	10.852202	23.003 ± 0.188	21.689 ± 0.086	21.076 ± 0.072	M, K
587732772665295407	180.55286	10.865665	22.517 ± 0.113	22.271 ± 0.129	22.177 ± 0.171	M, K
587732772665295122	180.54705	10.853076	20.925 ± 0.032	20.707 ± 0.036	20.534 ± 0.043	M, K
587732772665294873	180.54322	10.860261	18.944 ± 0.009	18.601 ± 0.008	18.474 ± 0.010	M, K

^aMagellan observations

^bKeck observations

Table 2. UVOT V-band Observations of GRB050408

t_{start} (s after burst)	Exp. (s)	Total Exp. (s)	t_{center} (s)	Limiting Mag (3σ)
2657.1	99.77	99.77s	2707.0	19.40 ± 0.35
13803.1	689.35	689.35s	14147.8	20.30 ± 0.25
37264.1	380.27	(combined)
40919.1	899.76	1280.03	40130.1	20.82 ± 0.25
59189.1	897.35	(combined)
70765.1	899.77	1797.12	64979.0	21.03 ± 0.25

Table 3. Optical/IR Observations of GRB050408

Filter	t_{burst} (d)	Mag	Ref	Comments
V	0.03133	19.4 ^a	This paper	UVOT re-reduction
V	0.16362	20.3 ^a	This paper	UVOT re-reduction
V	0.33899	18.5 ^a	Melandri et al. (2005)	
V	0.40548	21.4	Bayliss et al. (2005)	
V	0.46447	20.82 ^a	This paper	UVOT re-reduction
V	0.51747	22.069 ± 0.171	Milne et al. (2005)	
V	0.55185	21.7 ^a	Bayliss et al. (2005)	
V	0.63747	22.618 ± 0.191	Milne et al. (2005)	
V	0.75297	21.03 ^a	This paper	UVOT re-reduction
V	1.60747	23.48 ± 0.612	Milne et al. (2005)	
V	2.65673	24.067 ± 0.176	This paper	Keck
R	0.00007	11 ^a	Tamagawa et al. (2005)	
R	0.00123	10.9 ^a	Tamagawa et al. (2005)	
R	0.00101	16.2 ^a	Torii (2005)	
R	0.00416	16.2 ^a	Torii (2005)	
R	0.00730	17	Torii (2005)	
R	0.01330	19.1 ^a	Mizuno et al. (2005)	
R	0.05983	17.8 ^a	Kuroda et al. (2005)	
R	0.10000	20.4 ± 0.2	Misra et al. (2005)	
R	0.12927	20 ^a	Klose et al. (2005)	
R	0.15500	21.01 ± 0.07	Bikmaev et al. (2005)	
R	0.16122	20.5	de Ugarte Postigo et al. (2005)	
R	0.18208	21.1 ± 0.05	Bikmaev et al. (2005)	
R	0.20083	21.25 ± 0.2	Wiersema et al. (2005)	
R	0.20375	21.25 ± 0.05	Bikmaev et al. (2005)	
R	0.22458	21.27 ± 0.05	Bikmaev et al. (2005)	
R	0.24125	21.44 ± 0.06	Bikmaev et al. (2005)	
R	0.27292	21.37 ± 0.06	Bikmaev et al. (2005)	
R	0.28542	21.5 ± 0.06	Bikmaev et al. (2005)	
R	0.32580	21.584 ± 0.104	This paper	Magellan
R	0.33899	18.3 ^a	Melandri et al. (2005)	
R	0.34333	21.64 ± 0.07	Bikmaev et al. (2005)	
R	0.36458	21.6 ± 0.07	Bikmaev et al. (2005)	
R	0.47747	21.888 ± 0.15	Milne et al. (2005)	
R	0.53622	22.3 ± 0.3	Curran et al. (2005)	
R	0.57747	21.963 ± 0.129	Milne et al. (2005)	
R	1.14546	22.55 ± 0.35	Kahharov et al. (2005)	
R	5.03250	23.7 ± 0.2	Bikmaev et al. (2005)	

Table 3—Continued

Filter	t_{burst} (d)	Mag	Ref	Comments
I	0.21750	20.4 ± 0.3	Curran et al. (2005)	
I	0.32580	21.048 ± 0.123	This paper	Magellan
I	0.33899	17.9 ^a	Melandri et al. (2005)	
I	0.46930	21.47 ± 0.11	This paper	CTIO 1.3m
I	0.49747	21.305 ± 0.203	Milne et al. (2005)	
I	1.57747	22.288 ± 0.39	Milne et al. (2005)	
I	2.65673	23.012 ± 0.109	This paper	Keck
Z ^b	0.56190	21.8 ± 0.12	Flasher et al. (2005)	
J	0.33899	18.2 ^a	Melandri et al. (2005)	
J	0.46885	20.38 ± 0.28	This paper	CTIO 1.3m
J	0.59837	20.59 ± 0.19	This paper	PAIRITEL
H	0.59837	19.58 ± 0.153	This paper	PAIRITEL
K	0.57962	18.53 ± 0.176	This paper	PAIRITEL

Note. — All optical and NIR observations used in fitting. Data were taken from the GCN circulars and our own observations using Magellan, Keck (LRIS), and PAIRITEL.

^aUpper limit.

^bThe NIC-FPS (Vincent et al. 2003) Z was assumed to be equivalent to the SDSS z' .

Table 4. *Swift* XRT Aperture Photometry

Obs.	Duration (s)	Exposure (s)	C_A	C_B	Bkg. count density (10^{-2} counts pixel $^{-1}$)	GRB count rate (10^{-3} counts s $^{-1}$)
1a	358.5	358.5	100	2	0.056	396.0 ± 39.7
1b	2221.1	2153.8	315	20	0.182	207.4 ± 11.7
1c	1385.7	1358.9	130	8	0.084	135.6 ± 11.9
1d	1031.2	1025.5	63	6	0.028	87.0 ± 11.0
1e	4441.6	1049.7	57	7	0.014	76.9 ± 10.2
1f	614.7	536.5	16	1	0.070	42.0 ± 10.6
1g	2396.5	409.4	14	1	0.042	48.3 ± 13.0
1h	2391.1	287.3	8	1	0.028	39.7 ± 14.0
1i	1176.2	332.8	6	1	0.000	25.5 ± 10.5
1j	1553.7	429.5	16	1	0.070	52.4 ± 13.3
1k	2394.0	659.2	13	1	0.014	27.9 ± 7.8
1l	2388.4	639.3	22	5	0.056	48.3 ± 10.5
1m	1742.2	437.0	5	2	0.126	15.2 ± 7.3
2	52119.8	3399.1	19	2	0.294	7.68 ± 1.83
3	80975.1	2828.2	13	6	0.238	6.19 ± 1.82
4	59610.9	8361.7	25	10	0.630	3.98 ± 0.85
5	29603.5	3116.6	5	5	0.182	2.03 ± 1.02
6	180508.6	42828.5	27	80	2.18	0.65 ± 0.17
7	82821.9	21278.1	15	48	1.15	0.72 ± 0.26
8	86092.9	32161.4	24	51	2.14	0.79 ± 0.22
9	87416.5	33091.2	22	59	2.45	0.64 ± 0.20
10	35176.6	2943.5	0	12	0.22	—
11	133401.7	40145.1	28	120	4.45	0.51 ± 0.19
12	167985.7	21764.1	16	50	4.09	0.40 ± 0.26

Note. — For each (sub)observation, we list the duration of the XRT observation, the amount of exposure in the Photon Counting mode, the counts in regions A and B (see Fig 2), the space density of background counts, and the estimate of the GRB count rate using the expression in § 3.1. The count rate uncertainties are $1\text{-}\sigma$.

Table 5. Broken Powerlaw Model Parameters for the XRT

Parameter	Value
$\alpha_{x,1}$	$0.63^{+0.15}_{-0.19}$
$\alpha_{x,2}$	$1.08^{+0.05}_{-0.04}$
t_{break}	$1.26^{+1.19}_{-0.36} \times 10^4 \text{ s}$
A	$59.4^{+160}_{-48.1}$

Note. — 90% confidence intervals.

Table 6. X-ray Spectral Fit Parameters

Parameter	Before t_{break}	After t_{break}
Photon Index Γ	2.31 ± 0.75	1.33 ± 0.52
$N_{\text{H}}/10^{22} \text{ cm}^{-2}$	$1.5^{+1.1}_{-0.9}$	$0.52^{+0.45}_{-0.20}$

Note. — 90% confidence intervals.

Table 7. Absorption Line Summary

Ion	λ_{rest} (Å)	W_{rest} (mÅ)
Mg I	2852.964	1350 ± 70
Ti II	3073.877	170 ± 70
Ti II	3230.131	200 ± 40
Ti II	3242.929	570 ± 80
Ti II	3384.740	555 ± 40
Fe I	3021.519	300 ± 50

Note. — Errors in W_r do not include uncertainty due to continuum placement. For the weakest transitions, the systematic error will be comparable to the statistical error.

Table 8. Closure Parameters and χ^2 for Different Afterglow Models

Model	ν_c	[b,c]	Closure	p	Fit with extinction		
					β	A_V	χ^2/dof
ISM	B	$[-3/2, 0]$	-1.16 ± 0.15	2.05 ± 0.04	0.525	0.567	7.82 / 5
	R	$[-3/2, 1/2]$	-0.66 ± 0.15	1.71 ± 0.04	0.859	0.341	5.31 / 5
Wind	B	$[-3/2, -1/2]$	-1.66 ± 0.15	1.38 ± 0.04	0.192	0.786	11.3 / 5
	R	$[-3/2, 1/2]$	-0.66 ± 0.15	1.72 ± 0.04	0.859	0.341	5.31 / 5
Jet	B	$[-2, -1]$	-2.81 ± 0.20	0.79 ± 0.03	-0.10	0.972	15.3 / 5
	R	$[-2, 0]$	-1.81 ± 0.20	0.79 ± 0.03	0.394	0.660	9.05 / 5

Note. — Closure relations and parameters for a variety of afterglow models, after Price et al. (2002). None of the models are well-supported by our data without corrections for host extinction. The best-fit χ^2 when fitting for host extinction is given in the rightmost column; much better agreement is achieved.

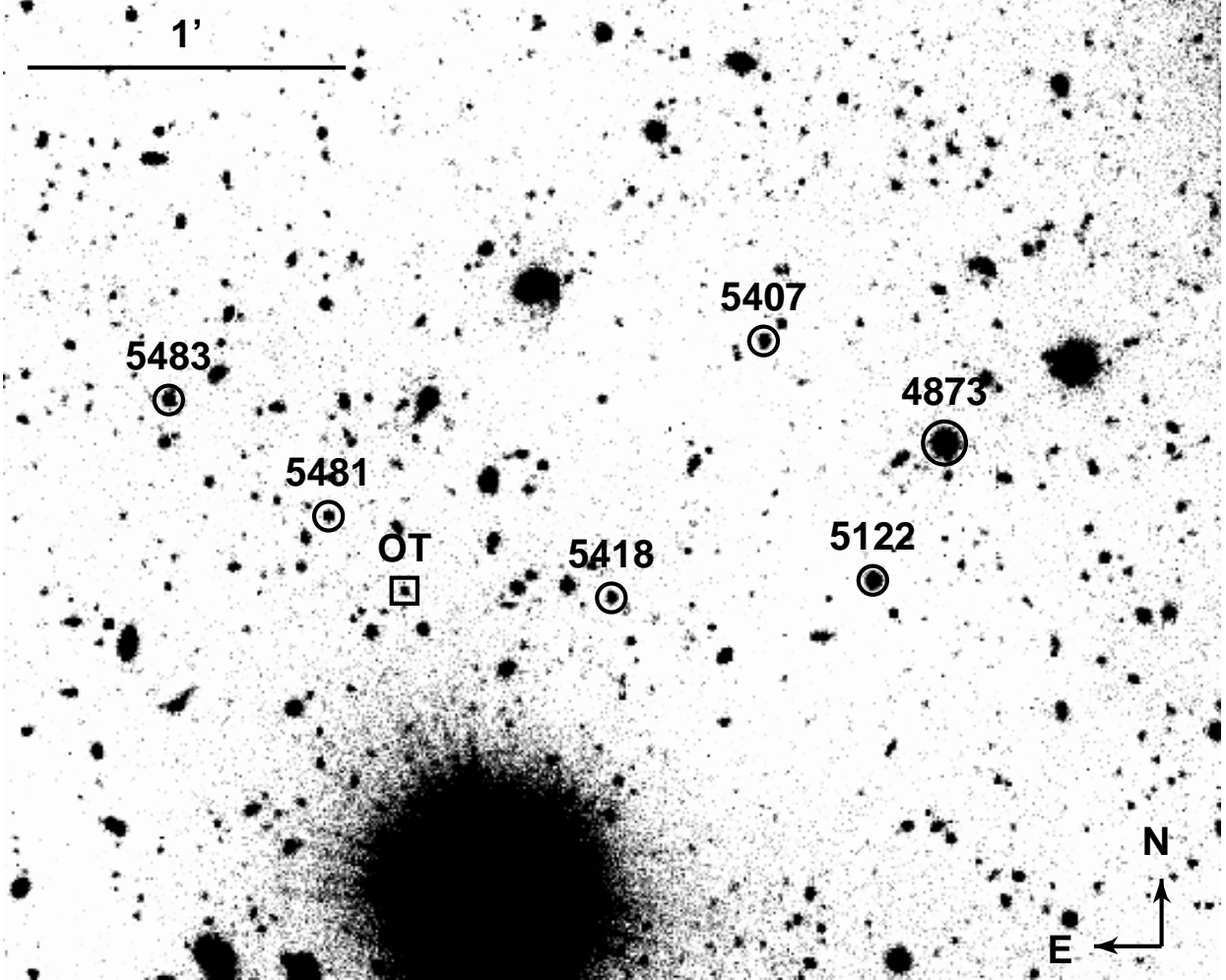


Fig. 1.— A Keck *R*-band image of the field of GRB 050408. The optical transient and nearby reference stars (see Table 1) are marked.

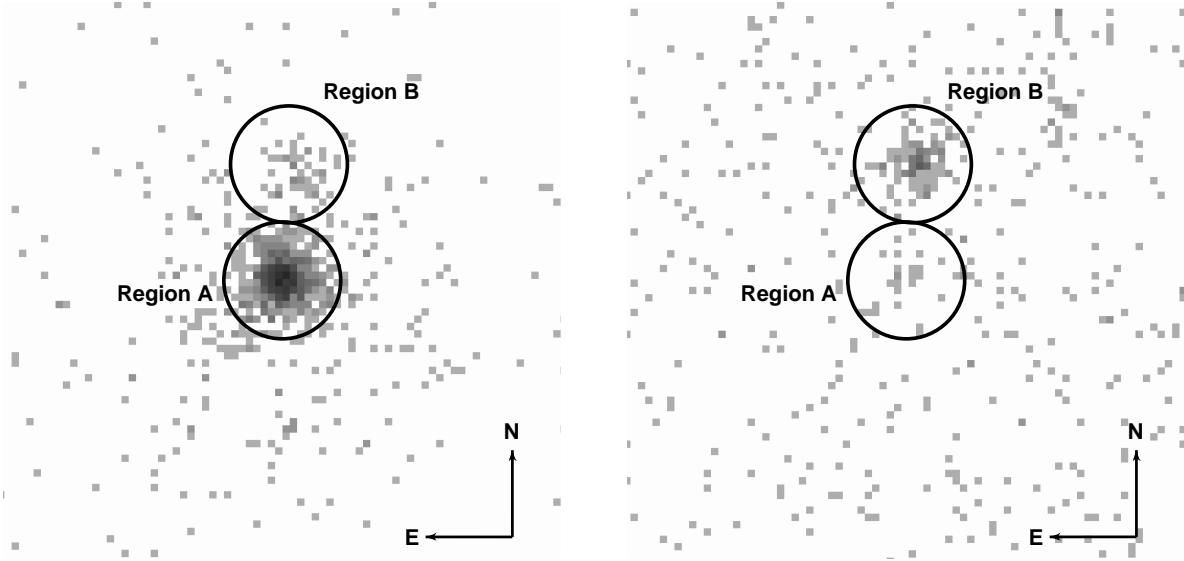


Fig. 2.— Images of the *Swift* XRT data from first observation (starting at 17:05:24 on 2005 April 8, left) and eleventh observation (starting at 02:36:32 on 2005 May 7, right). Each image is $3'$ on a side. The extraction regions A (centroid of RA = 12:02:17.594, Dec = +10:51:06.60) and B (centroid of RA = 12:02:17.448, Dec = +10:51:44.06) are discussed in the text.

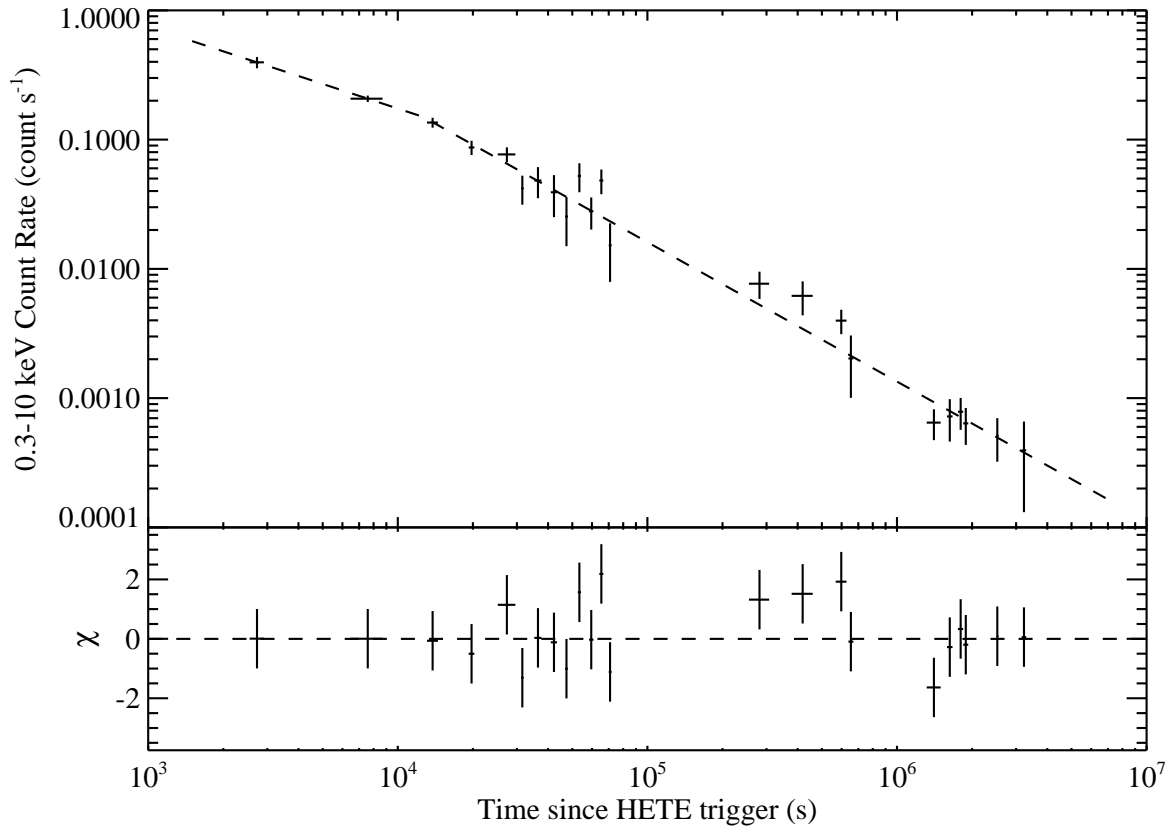


Fig. 3.— GRB X-ray countrate (crosses) and best fitting broken power law model (dashed line). The horizontal bars of the crosses represent the length of the observation interval.

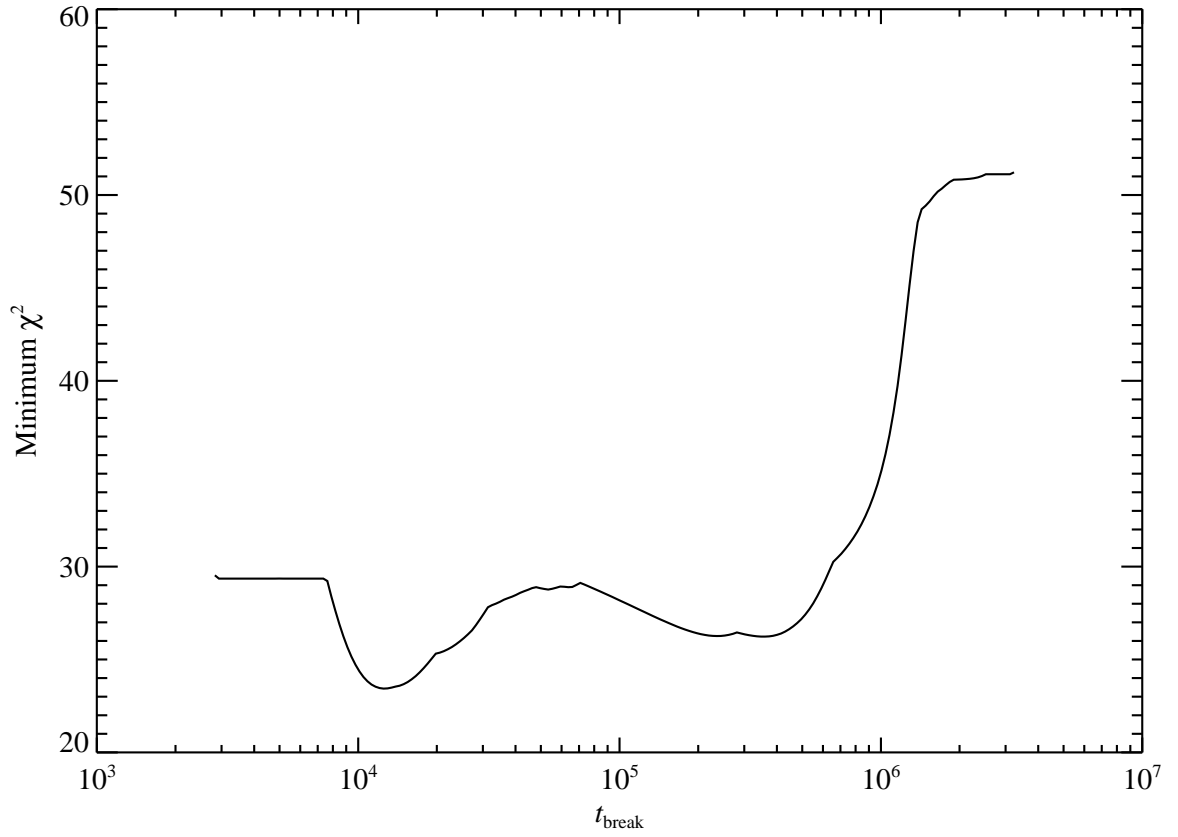


Fig. 4.— The minimum χ^2 value found as a function of t_{break} . The flattening at early and late times is due to the lack of points at these times, making the fit essentially a single powerlaw.

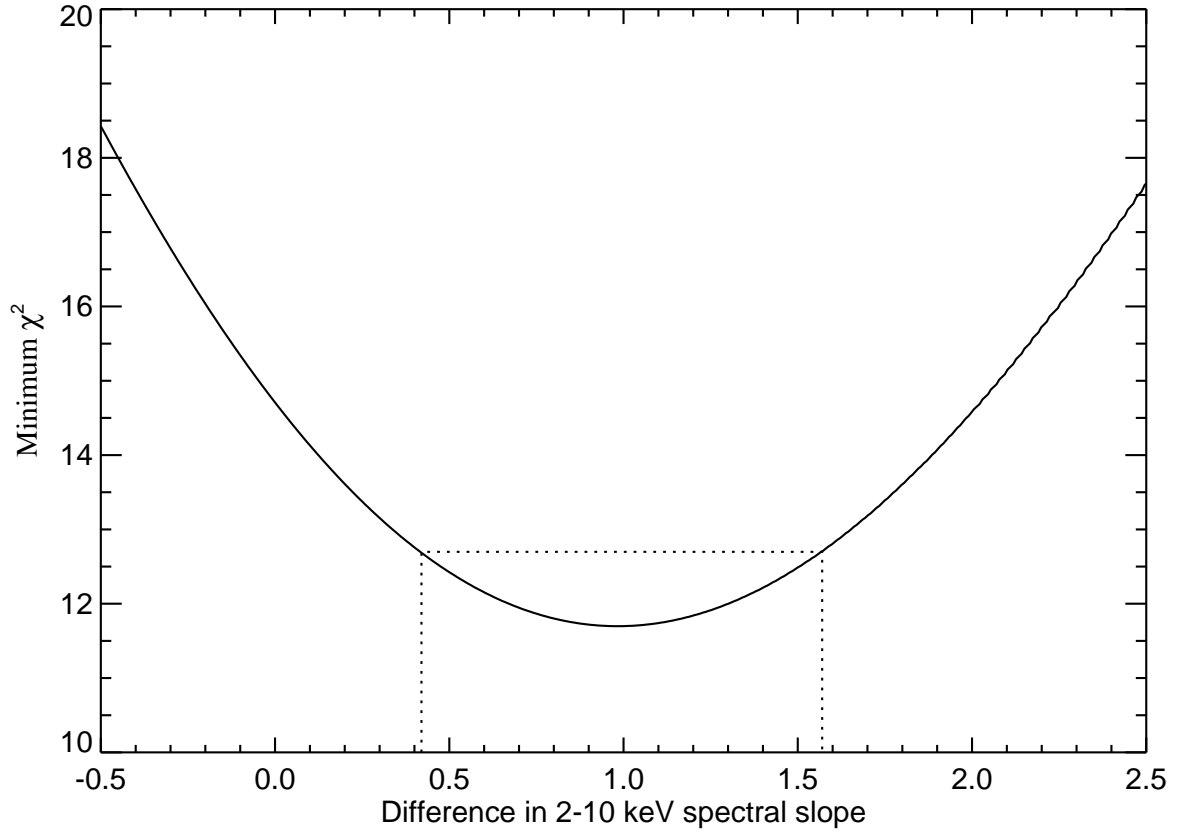


Fig. 5.— The minimum χ^2 value found in a joint spectral fit of the 2–10 keV data before and after t_{break} as a function of the difference in photon indices of the two powerlaw models. The dotted line corresponds to the 1σ errors.

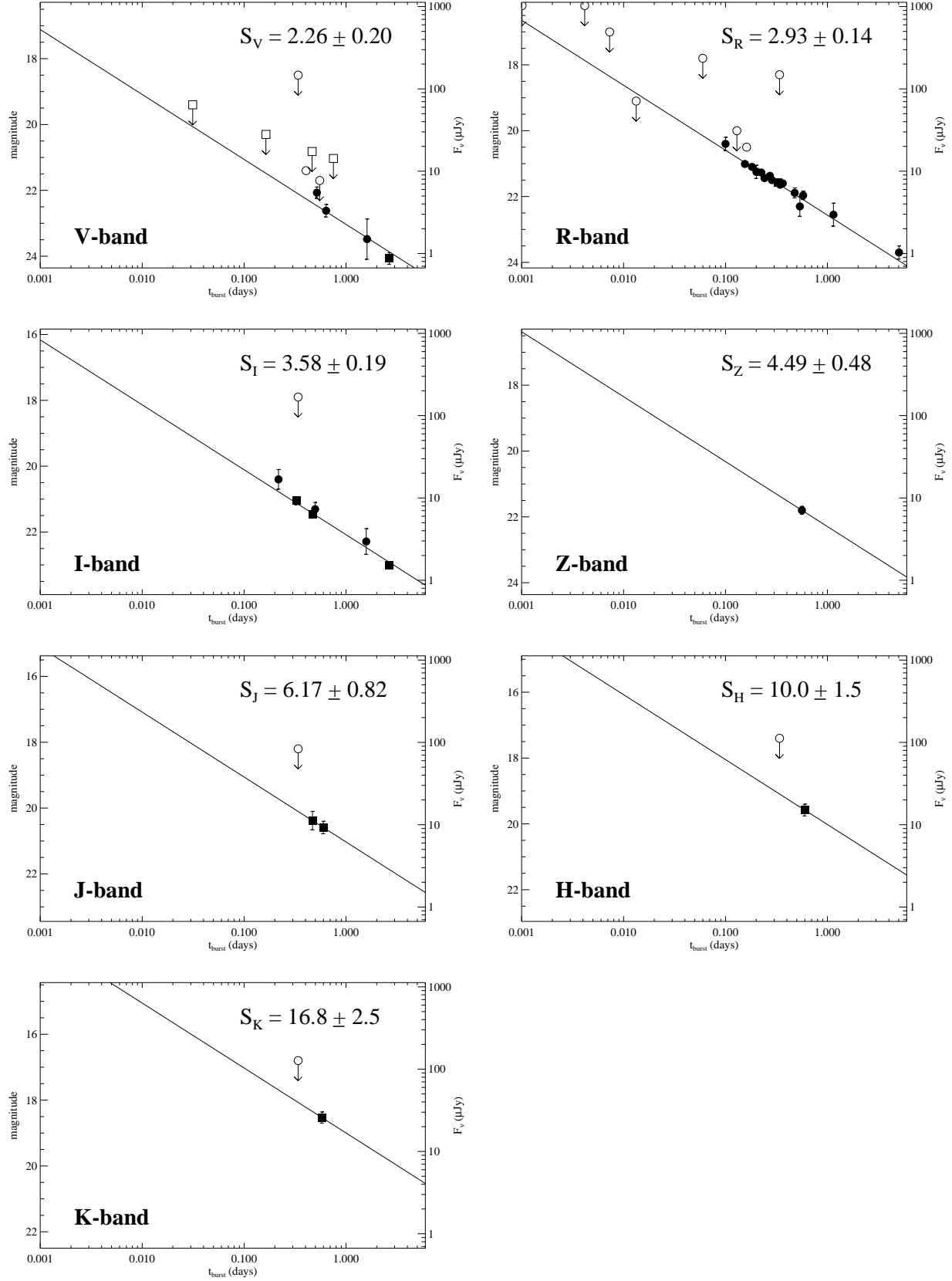


Fig. 6.— The *VRIzJHK* light curves of GRB 050408. GCN observations are circles, our Keck, Magellan, PAIRITEL, and ANDICAM observations presented in this paper are squares. Filled points are detections, while open points are upper limits. The expected flux at $t = 1$ day (before correction for Galactic extinction)

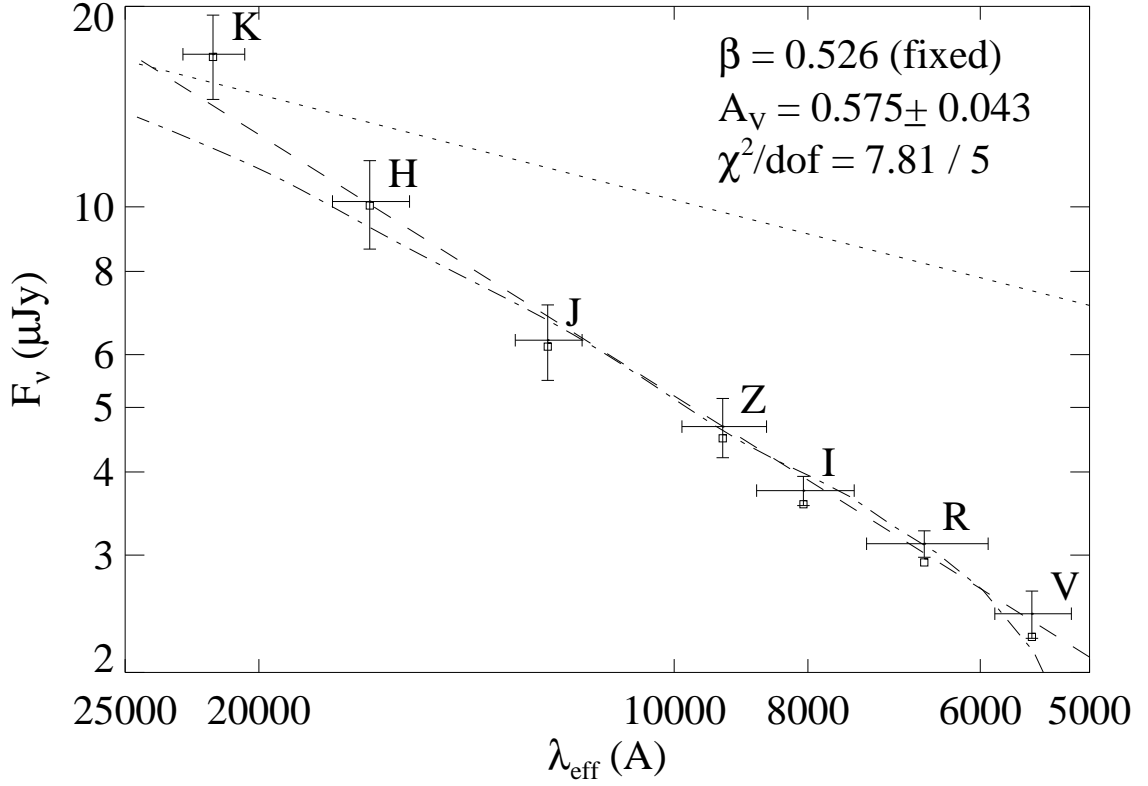


Fig. 7.— Broadband spectrum of the afterglow of GRB050408 at one day after the burst, assuming a uniform power-law decay in all bands. Two model spectra are fit to the data: an unextincted power-law (with arbitrary spectral index β), and a power-law (with $\beta = 0.53$, fixed according to the value inferred from the light curve) with extinction fit. The unextincted fit gives a value of $\chi^2 = 3.19$; the fit with extinction a value of $\chi^2 = 7.81$.

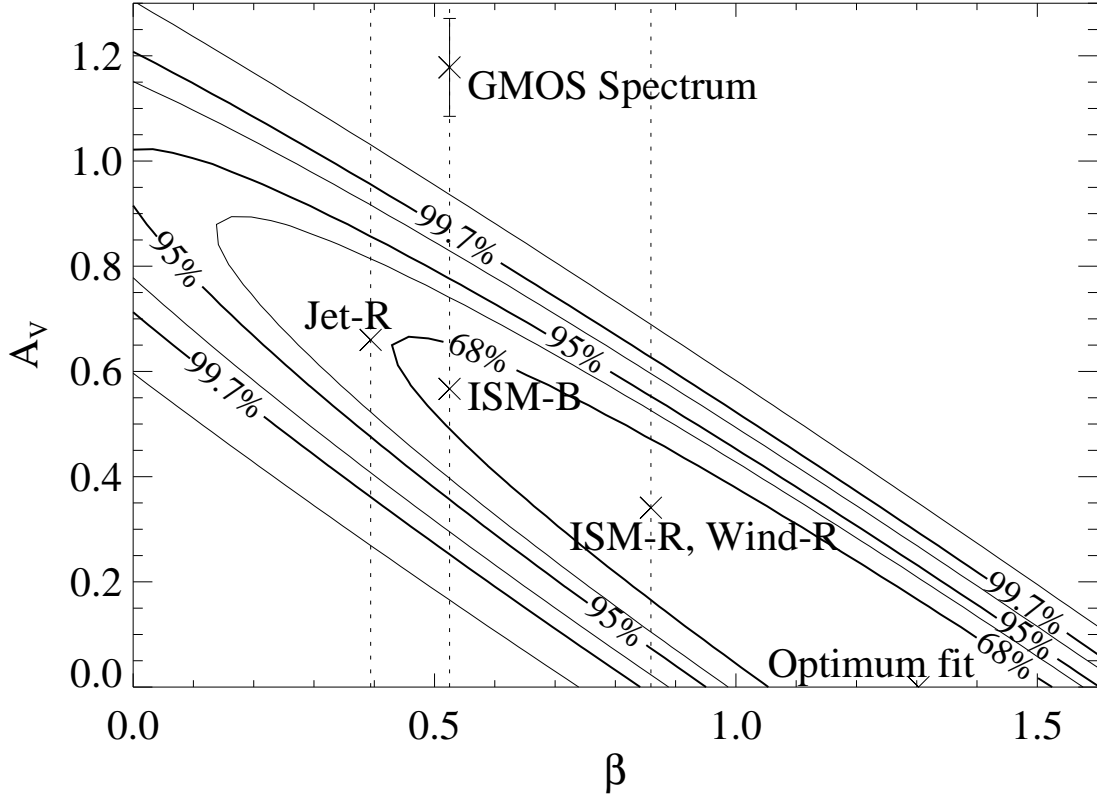


Fig. 8.— 1-, 1.5-, 2-, 2.5-, 3-, and 3.5- σ confidence contours for different possible values of the intrinsic β of the afterglow and the host-galaxy A_V , fitting to the broadband spectrum. In addition, we have overplotted dashed lines corresponding to the values of β predicted from the rate of decay of the light curve assuming various models, and the best-fit value along those lines. Also overplotted is the point inferred from the GMOS spectrum when fit with extinction.

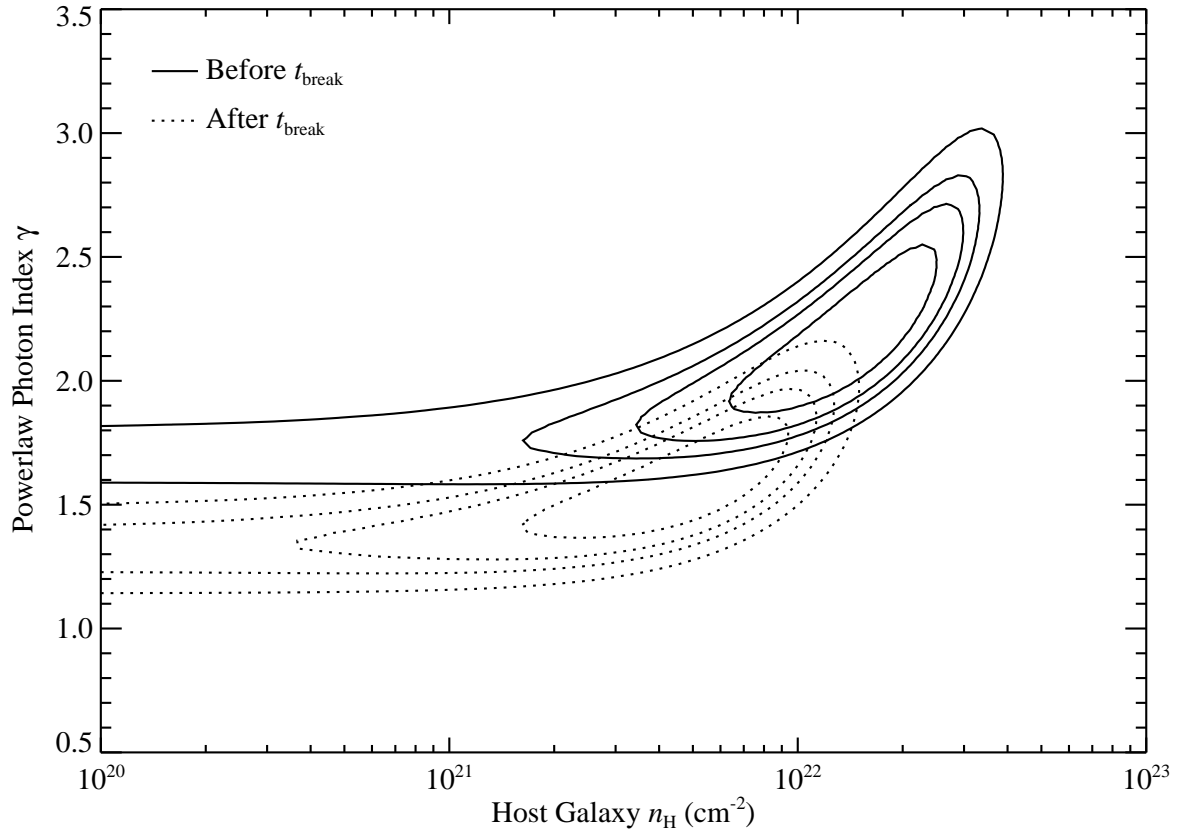


Fig. 9.— The 68%, 90%, 95%, and 99% joint confidence intervals for the power-law photon index of the GRB and the column density of host galaxy.

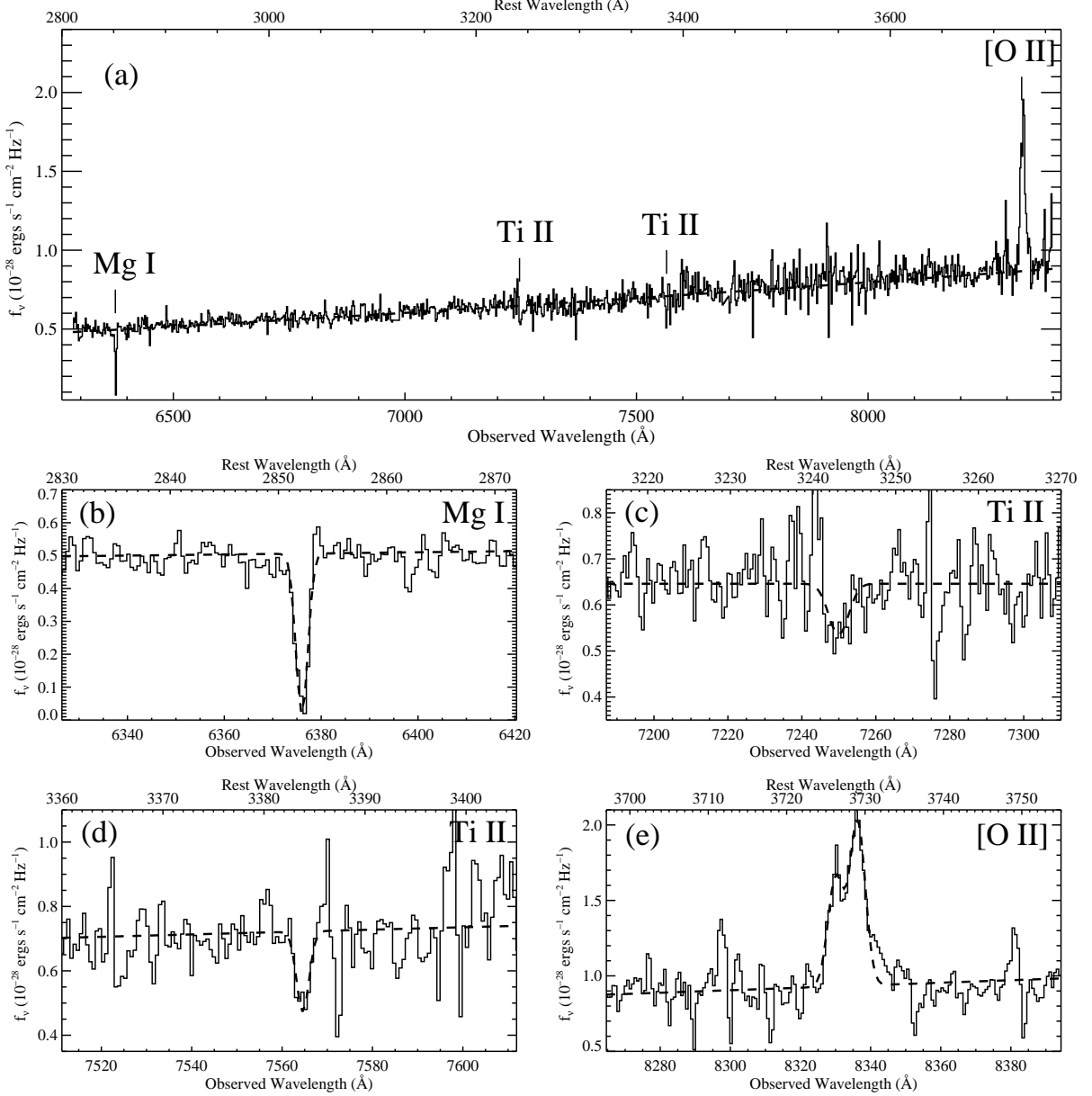


Fig. 10.— Optical spectrum of GRB 050408. (a) shows the entire spectrum with Ti II, Mg I, and Fe I absorption lines and [O II] emission lines. A powerlaw is fit to the continuum and shown by the dashed line. The powerlaw fit yields $p_{\text{spec}} = 5.22 \pm 0.58$ without host galaxy reddening and $p_{\text{spec,dust}} = 2.05 \pm 0.23$ if $A_V = 1.18$ in the host galaxy. (b)-(e) show the Mg I, Ti II $\lambda 3242$, Ti II $\lambda 3384$, and [O II] transitions in detail. The dashed lines in these subpanels are Gaussian fits to the lines. The Ti II $\lambda 3242$ line is blended with a bright sky line at 7245 Å.

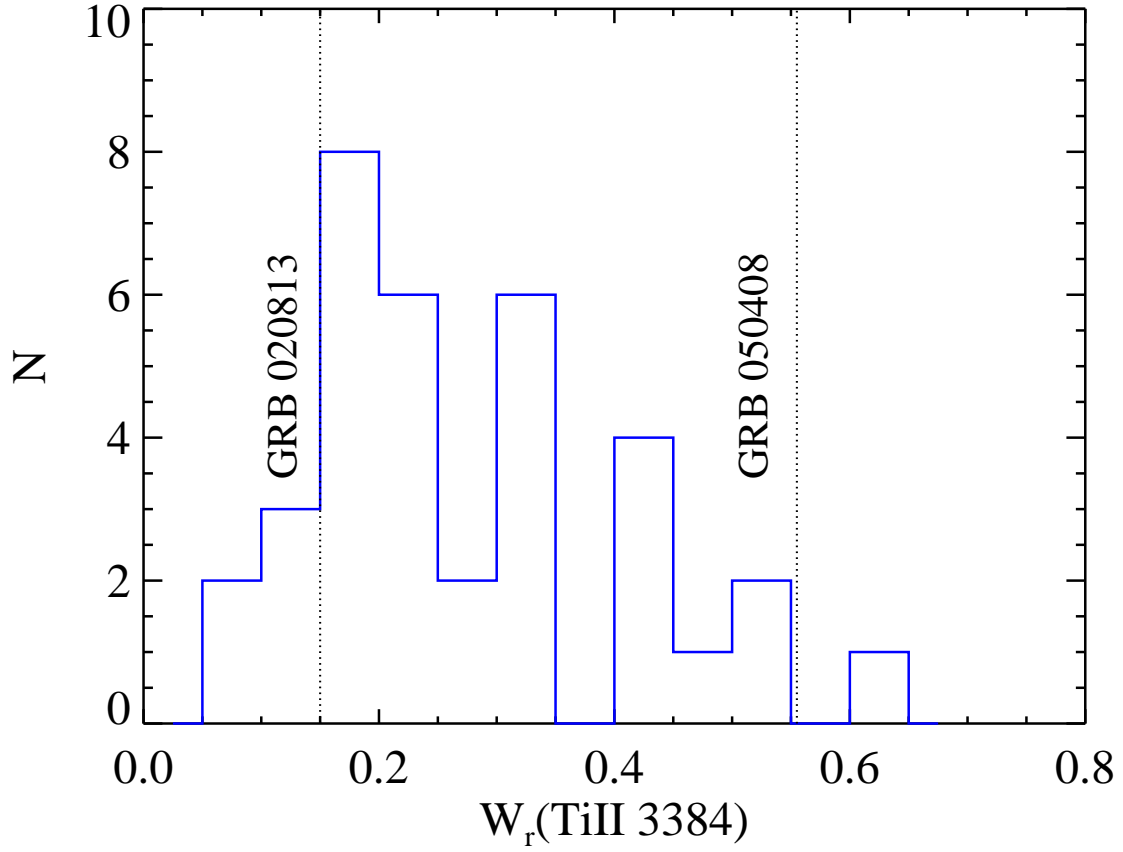


Fig. 11.— Histogram of $W_r(\text{Ti II } \lambda 3384)$ values identified from 4450 strong Mg II systems in the SDSS Data Release 3 (Prochter et al. 2004). The observed values in the afterglows of GRB 050408 and 020813 (Fiore et al. 2005) are given by the vertical dashed lines. The figure demonstrates that random sightlines through the Universe very rarely penetrate gas with $W_r(\text{Ti II})$ comparable to GRB 050408.